

FIELD FLUCTUATION AND BEAM SCREEN VIBRATION

MEASUREMENTS IN THE LHC MAGNETS*

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Abstract

We present experimental methods and results of magnetic field fluctuation and beam screen vibration measurements in the LHC magnets. These noises can lead to an emittance growth in proton beams if they have spectral components at the betatron lines. A preliminary estimates of the effects are given.

1. EMITTANCE GROWTH DUE TO MAGNETIC FIELD FLUCTUATIONS

Magnetic field fluctuations at the betatron frequency will cause miniscule turn-to-turn variation of the bending angle $\delta\theta = \theta_0 \delta B/B$ in each dipole magnet and that will lead to the horizontal emittance growth [1, and Ref therein] :

$$d\varepsilon_N/dt = f_0 \gamma \beta_{ave} (\delta B_{eff}/B)^2 / (2N) \quad (1)$$

where f_0 is the revolution frequency, γ is the relativistic factor, β_{ave} is average beta-function, N is the total number of dipoles and $\delta B_{eff}/B$ is the effective rms amplitude of the field fluctuations which for “colored” noise with power spectral density $S(f)$ can be defined as

$$(\delta B_{eff}/B) = [2 f_0 \sum S(f_0 |n-Q|)]^{1/2} \quad (2),$$

Q is the horizontal tune. The tolerance for the LHC is very tight [1] $\delta B_{eff}/B \sim 3 \times 10^{-10}$ will double the emittance over 10 hrs of store time. Tevatron dipole field fluctuation measurements [1] have shown that the amplitude of field fluctuation falls with frequency and, thus, lower betatron frequency of 3.4 kHz in the LHC (vs 20kHz in Tevatron) is to disadvantage. The turbulence of the He flow may lead to the field fluctuations, too – in the case of the LHC it's of a big concern because the beam screen inside the magnet aperture will be cooled by 5-20K Helium flow. The broad band Helium turbulence leads to jitter of the light beam screen walls, the screen changes its shape due to quadrupole oscillations that results in the magnetic field fluctuations because of the “frozen magnetic flux” effect at high frequencies. Indeed, the beam pipe radius variation of δR will result in the field variation of $\delta B/B = -\delta R/R$. For the LHC dipole, the beam screen radius is $R=25$ mm, and one needs only $\delta R=10^{-5}$ μm to get the value of $\delta B/B=3 \times 10^{-10}$. Similar effect – induction of dipole magnetic field can be caused by fast beam screen motion in the quadrupole magnets – see Fig.1.

Similar effect of turn-by-turn field variation may be caused by vibration of quadrupoles, corresponding theory and estimates can be found in e.g. [2], some experimental results in [3]. Notably, the tolerances on vibrations for arc quadrupoles are in the range of few Angstroms (0.1nm) at the betatron frequencies.

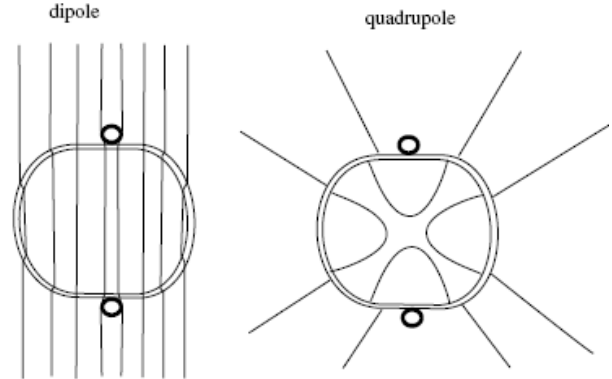


Fig.1: “Frozen” magnetic field lines in the LHC beam screen with shape oscillations (dip), and vibrations (quad).

2. FIRST MEASUREMENTS OF FIELD FLUCTUATIONS

Calibration of coils, beam screen resonances

Five coils used for B-field fluctuation measurements were calibrated at the Bld.181 test stand. The stand consisted of pair of Helmgoltz-like dipole coils received FNAL 20x120cm 100 turns each placed 20 cm above one another, excited by Agilent 10 V AC function generator. The current in the excitation coil was measured as voltage across 1 Ohm resistor. Resistance of the excitation coils was 5.5 Ohm. They create vertical magnetic field in between them of 2.95+-0.1 G/A at the frequency of the generator. See calibration results in the Table below.

	Coil#1&2	Coil#3	Coil#4	Coil#5
C, V/G/Hz	6e-3	2e-3	1.3e-4	1.3e-4
Max.freq,kHz	6	2	20	40
R, Ohm	332	4500	600	300
#of turns	930	256	150	36
Length, cm	50	200	24	120
Area, m^2	10	7.66	0.32	0.31

About 2 m long piece of the LHC dipole beam screen was inserted inside 10-cm long B=700 G permanent dipole magnet. Coil #4 was set inside the screen at the location of the magnet. Then, the beam screen was pinged (by a screwdriver) and the coil detected B-field ripple induced by the waves in the screen. The FFT of such signals and spectrum of the noise (no ping) are presented

in Fig.2. Notable peaks due to the free standing beam screen resonances are at frequencies 112Hz, 200Hz, 260Hz, 1070Hz, 1500Hz, 3500Hz. Rms noise amplitudes at frequencies >1000hz are about 50 uV.

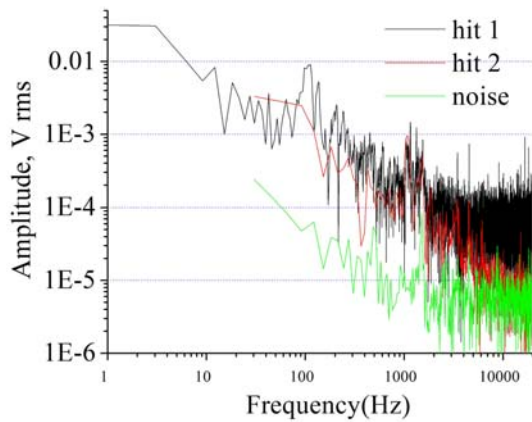


Figure 2: Spectra of the signals induced by hitting beam screen immersed in 700G B-field and of the noise.

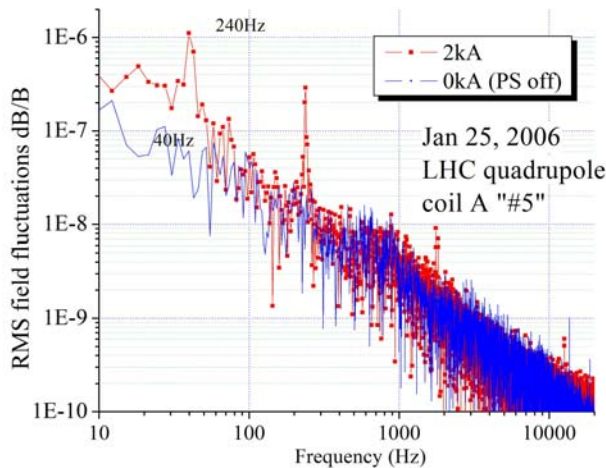


Figure 3: Signal from a coil #5 placed in SC MPY quadrupole at 2kA.

Magnetic field fluctuations in MQY quad

On Jan 25, 2006, we got several hours to measure field fluctuations in the “block 4” vertical cryostat facility where a MQY quadrupole was installed and equipped with rotating coils of type as “coil #5”. The quadrupole was immersed in 4.5K Helium bath. There was no beam screen installed in the quad. Maximum current in the quadrupole was limited to 2kA (out of max 3.6kA which corresponds to 160 T/m gradient). Voltage from “coil A” (most radially outward coil) was recorded by Tektronix 3062 digital scope (20kHz LPF was used). The B-field at the location of the coil was about $B=2T$, then, the relative field fluctuation amplitude can be estimated as using known coil coefficient as $\delta B/B = \delta V/C/f[Hz]/B$ – see results in Fig. 3. One can see peaks in the spectrum at 40 Hz, 240 Hz and 1750 Hz and 1820 Hz. Note, that at the frequencies above few kHz, the noise signal (recorded with the quad power supply turned off) takes over the

2kA signal. A higher resolution ADC and more averaging helped to improve signal to noise ratio in subsequent measurements.

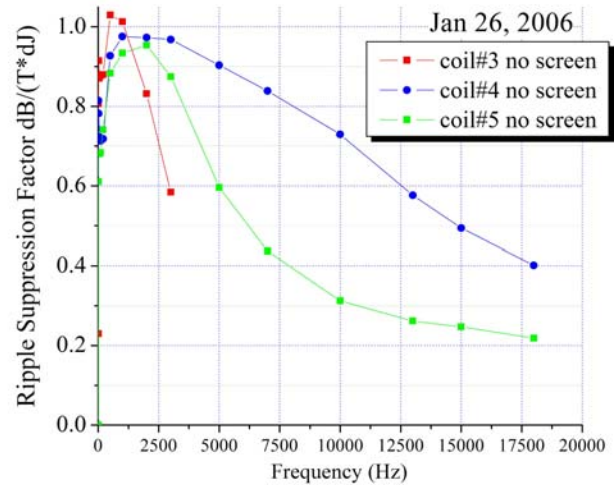


Figure 4: B-field ripple suppression vs frequency.

Magnetic field ripple from current

If the magnet current is not stable, the magnetic field inside the bore will fluctuate as well. We excited a warm LHC dipole in Bld.181 by $dU=10V$ AC voltage from a function generator and recorded voltage induced in the measurement coils #3,4, and 5. The dipole current amplitude is $dJ=dU/(6Ohm+2*3.14*f[Hz]*0.1Hn)$. Signal induced in the measurement coil is approximated as $dV=K*dB[G]$ (that is not exactly true - see paragraph 2a). The function $R=0.7[G/A]*dJ*K/dV$ is plotted in Fig.4. Coefficients K for each coil were adjusted “by hand” in order R to be 1 at low frequencies. Difference in suppression factors measured by different coils could be explained by significant interference due to stray-capacitance induced signals (though, not everything is understood yet). In any case, suppression factor is about 0.9 at 3kHz and about 0.3-0.7 at 10 kHz. For reference, skin depth in SS is about 7 mm at 5kHz.

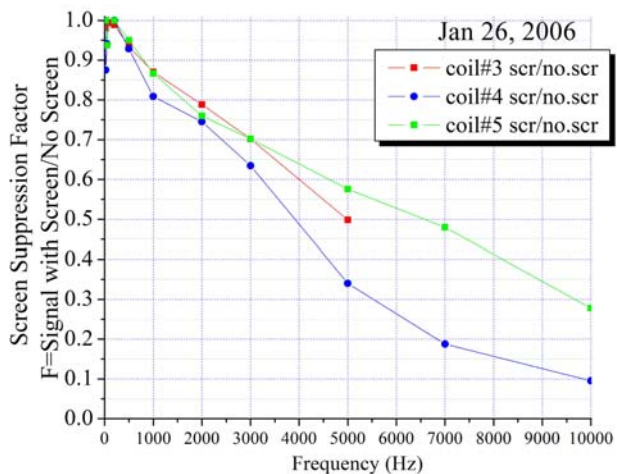


Figure 5: Additional field suppression by beam screen vs frequency.

Field suppression by beam screen

The same measurements as above were performed with beam screen. Ratios of signals from all three coils with and without the beam screen are presented in Fig.5. One can see that the screen provides additional reduction of about 0.7 at 4kHz and about 0.1-0.3 at 10kHz. Skin depth in copper at 5kHz at room temperature is about 1mm, so at 2K it will be ~5-7 times thinner or ~150-200 μm , which is still several times bigger than 50 μm thickness of the Cu layer on inner surface of the screen – thus, one should not expect significant difference in the screen effect at room and nominal temperatures.

3 SCREEN VIBRATIONS

Direct measurements of screen vibrations were performed using very light (30g) and small (20 mm high) EndevCo 2272 piezo accelerometer (suitable for operation at He temperatures) and 2775B Signal Conditioner.

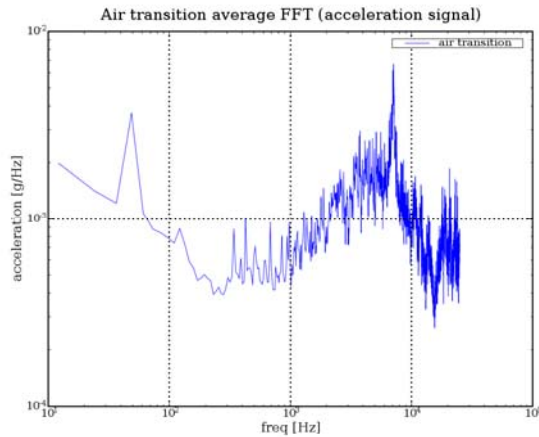


Figure 6: Spectrum of piezo-accelerometer signal induced by airflow in the beam screen cooling channel

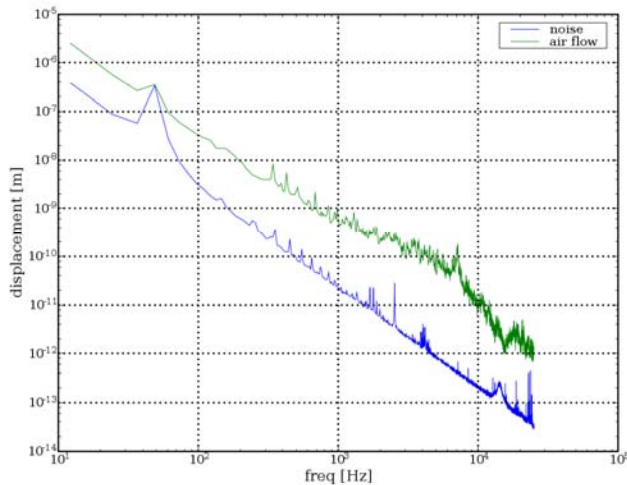


Figure 7: Additional field suppression by beam screen vs frequency.

The accelerometer sensitivity is 11.568 pC/g, accelerometer capacitance 2700 pF. Output voltage of the signal conditioner was digitized by HP3458A digital voltmeter (DMM) with 19 bit resolution at 50 kHz sampling rate. The accelerometer was placed inside the beam screen and tightly connected to it using a specially made fixture.

We did not have a possibility to measure screen vibrations at cryogenic temperatures. Instead, we installed the beam screen inside a warm LHC dipole and blew up air thru the cooling channels of the beam screen using 8 atm air compressor. One can see in Fig. 6 that the air flow excited screen vibrations in the range of frequencies from 1kHz to 10 kHz.

Spectra of displacement x – calculated as $x=a/(2 \pi f)^2$ where a is the measured beam screen acceleration, and f is the frequency – are shown in Fig.7. The blue curve represents the spectrum of the noise in the system of “accelerometer, signal conditioner, and DMM” measured when the air compressor was off. The green curve represents the measured vibration amplitude with full scale air flow. One can see that at the lowest LHC betatron frequency of $f=3.4\text{kHz}$, the screen vibration amplitude is about $\delta R=2 \times 10^{-4} \mu\text{m}$ that is equivalent to field fluctuations $\delta B/B=60 \times 10^{-10}$ or about factor of 20 above the tolerance.

In summary, we have measured suppression of the transfer ratio of “current fluctuations/field fluctuations” for the LHC dipole in the frequency range from 10Hz to 25kHz. Reduction of the current induced field fluctuations by the conducting materials of the LHC beam screen was found to be ~0.5-0.6 at the lowest LHC betatron frequency of $f=3.4\text{kHz}$. The only measurements of the field fluctuations with pick up coils inside energized LHC SC magnet (quadrupole) were dominated by noise and revealed few peaks in the spectrum at 40 Hz, 240 Hz and 1750 Hz and 1820 Hz. Effect of the 8 atm airflow thru cooling channels of the warm LHC beam screen inside dipole magnet showed vibration amplitudes in the frequency range from 1kHz to 10kHz factor of 20 above the collider tolerance. Our main goals for the next studies are to measure $\delta B/B$ and vibration spectra inside 8.3T LHC SC dipole with beam screen installed and cooled by LHe.

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